Shedding Light on Black Holes

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Some of the brightest and most extreme objects in the universe are powered by matter falling into a black hole. They range from stellar-sized black holes formed at the end of the life of a massive star to supermassive black holes in the centres of galaxies that often outshine the entire galaxy in which they reside. Massive black holes in the centres of galaxies release so much energy that they play an important role in how the galaxy around them evolves. As well as being impressive objects in their own right, black holes provide unique laboratories for testing strong gravity and matter under extreme conditions.

What is a Black Hole?

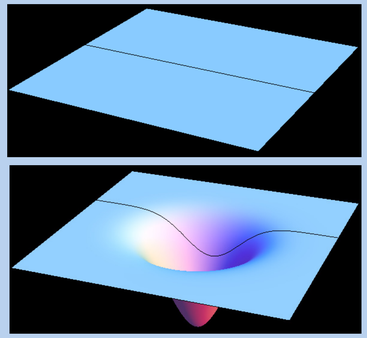
What's the big attraction with gravity?

Black holes are a natural consequence of Einstein's theory of gravity, General Relativity. Rather than thinking of gravity as a force in the conventional sense, General Relativity says that it is a result of spacetime curving.

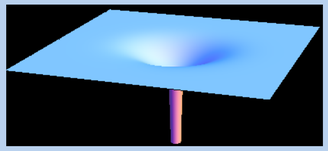
In normal, flat space, free particles that are not subject to any force travel in a straight line – the shortest possible path between two points (a *geodesic*). When a force is applied to the particle, it can be made to deviate from this straight line or made to speed up or slow down.

The presence of matter causes spacetime to curve around it (imagine placing a heavy ball on a flexible rubber sheet, though extending this idea to bending to 4-dimensions of space and time). Free particles will still travel on geodesics, however now, these shortest paths between two points curve with the spacetime towards the mass that is causing the curvature. This bending of the particle's trajectory towards the mass appears as the force of gravity.

Mass curves time as well as space. A clock closer to a massive object will tick more slowly than one further away and because it is space itself curving, even light (which is classically considered to have no mass and therefore no gravitational attraction) can be seen to bend towards to massive object (so-called *gravitational lensing*).



(Top) In a flat spacetime (a 2 dimensional space is shown here), free particles travel along geodesics that are straight lines.
(Above) Matter causes spacetime to curve around it. In this curved spacetime, the path curves causing an otherwise free particle to be pulled towards the mass. We see this as gravity.



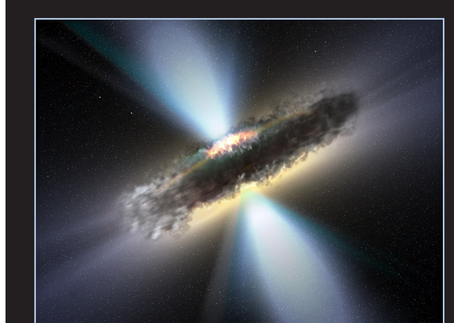
When matter is extremely dense (i.e. there is a critical amount of matter in a confined space), the curvature created in spacetime is so extreme that beyond a certain point, the *event horizon*, nothing can return. All paths lead to the centre of this distortion so not even light can escape from within this surface. This is a black hole.

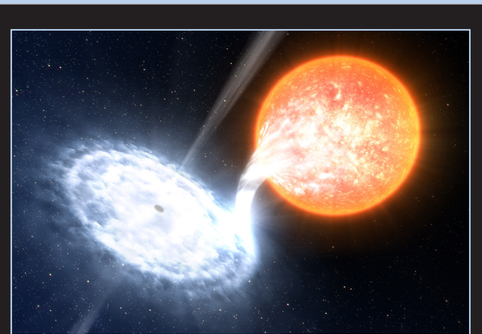
(Left) Extremely dense matter causes extreme curvature in spacetime from which nothing can escape: A black hole.

Where do we find black holes?

Every galaxy harbours a supermassive black hole at its centre that is between a million and a billion times the mass of the Sun (which itself is 2×10^{30} kg). Even our own galaxy, the Milky Way has a black hole at the centre (which we know is there from its pull on stars at the galactic centre!). When these enourmous black holes release energy by pulling in matter, they can outshine all of the stars in the galaxy in an active galactic nucleus (AGN).

Black holes can also form when massive stars come to the ends of their lives. Throughout the life of the star, the pressure of the hot gas pushing outwards prevents the gas collapsing under its own gravity. When the star runs out of nuclear fuel to burn, it cools down so there is nothing to stop gravity pulling the gas together. The gas falls inwards as the star collapses, releasing energy as it does so. For massive stars, about ten times the size of our Sun, such a huge amount of energy is released that it blows off the outer layers of the star in a violent supernova explosion. The remaining mass (between 1.5 and two times the mass of the Sun) is still large enough that no force is strong enough to stop it collapsing down infinitely to a very dense point (or *singularity*), leaving a black hole. These stellar mass black holes are most interesting when in orbit around another star from which they takes material in a black hole binary.





(Far Left) An active galactic nucleus. The galaxy contains a supermassive black hole at the centre which is taking in dust and gas and emitting large amounts of energy. The central region is surrounded by a dusty torus.
(Left) A black hole binary. The black hole is in a binary orbit with a companion star from which it is taking material. This material spirals in to the black hole through an accretion disc, a process which emits huge amounts of energy in visible light, ultraviolet and X-rays.

Energy Release

When material falls under gravity, it releases energy. When dust and gas fall in the extremely strong gravity around a black hole, enourmous amounts of energy are liberated. The process of material falling onto an object under gravity is known as *accretion* and accreting material tends to flatten into a disc that spirals into the black hole (an *accretion disc*).

While no energy can escape from beyond the event horizon around the black hole, energy is released from the material as it falls in. Accretion onto a black hole is the most efficient process for emitting energy from matter in the Universe, releasing up to 40% of the rest mass energy of the material falling in.

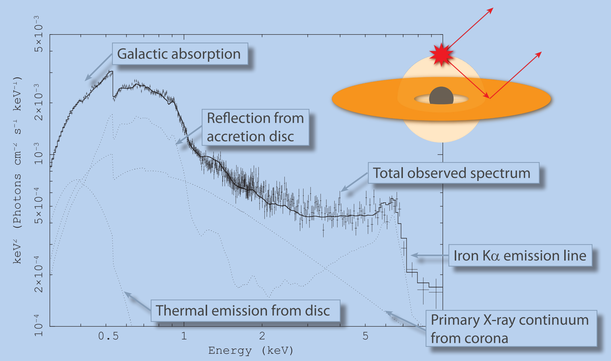
Friction between parts of the accretion disc causes it to heat up and when matter heats up it glows, emitting *black body radiation*. The material reaches around 10,000,000°C causing it to not only emit infrared and visible light, but also ultraviolet light and some X-rays.

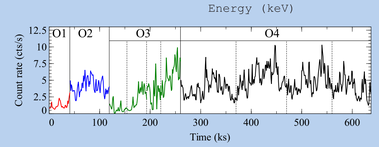
Furthermore, the hot accretion disc becomes ionised (electrons spearate from atoms) meaning that magnetic fields are 'frozen in' to the disc. As the material orbits the black hole, magnetic field lines are tied into knots and can snap (a process called reconnection) releasing energy which accelerates nearby particles to ulltra-high energies (like a solar flare). These particles can collide with low energy photons (particles of light) and boost their energies, emitting enourmous amounts of energy from a hot corona around the black hole in the form of X-rays which we observe.

(Above) Enormous amounts of energy are emitted as material spirals in to a black hole. In some cases, the black hole can launch jets of high energy electrons and positrons travelling at almost the speed of light.
(Left) Particles are accelerated by magnetic fields anchored into the accretion disc around the black hole.

What Can We Learn?

We have learned an phenomenal amount about black holes and how energy is released from accreting material using the large X-ray telescopes XMM-Newton (European, launched in 1999), Chandra (USA, launched in 1999) and Suzaku (Japan, launched in 2005).





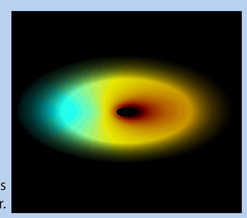
(Above) The X-ray spectrum of the AGN 1H 0707-495, showing origins of the components.
(Left) The change in brightness of 1H 0707-495 over time which can help us constrain important properties of the black hole.

Studying the X-ray spectrum of an accreting black hole reveals X-rays of different energies emitted by different processes. It is possible to see both the thermal X-rays emitted from the surface of the accretion disc and the X-rays emitted from high energy particles in the hot corona around the black hole. In addition, the X-rays emitted from the corona can be reflected from the accretion disc.

Reflection from the accretion disc imprints a number of atomic features on the spectrum we observe, not least emission lines. When atoms are excited, their electrons emit light at very specific energies (colours). It is why different metal compounds glow different colours when heated *e.g.* sodium street lights appear orange.

In the laboratory, atoms emit light in very narrow energy bands. Close to a black hole, however, the spacetime is stretched and time runs more slowly. This causes the light from close to a black hole to be shifted to lower energies (visible light becomes more red). In addition to this, the reflecting material in the accretion disc orbits the black hole and its motion causes the light to be Doppler shifted to higher energies as it comes towards us and lower energies as it moves away. These effects smear the narrow atomic emission into a broad energy range.

Looking at the X-rays received from atomic transitions at different energies gives us an indication of whereabouts they were emitted with respect to the black hole. We can see light emitted from material just moments before it crosses the black hole's event horizon, allowing us to probe the extreme conditions and strong gravity close to the black hole. By comparing what we see with theoretical predictions, we can learn a great deal about the system, including whereabouts the coronal X-ray source is located and how the energy is actually emitted.



(Right) Emission from different parts of the accretion disc are shifted to different energies observed by telescopes on Earth. Red indicates shifts to lower energies and blue to higher.

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